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MULTIRESPONSE OPTIMIZATION OF PROCESS VARIABLES OF POWDER MIXED ELECTRICAL DISCHARGE MACHINING ON INCONEL-600 USING TAGUCHI METHODOLOGY

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ABSTRACT

In the present work, performance parameters for the machining of Inconel-600 using Powder Mixed Electrical Discharge Machining (PMEDM) have been optimized using the Taguchi methodology. Experiments have been conducted by the Taguchi L_9 orthogonal array. Tungsten carbide powder particles have been used as a powder additive. Material removal rate (MRR) and tool wear rate (TWR) have been considered as a measure of machining performance with three different control parameters such as peak current, pulse on-time (T_{on}) and pulse off-time (T_{off}). The results indicated that the use of tungsten carbide as a powder additive particles significantly improved the response parameters, i.e. increases the material removal rate and reduces the tool wear rate as compared with the outcomes coming from without using powder additive in EDM oil. The results have been analyzed with and without powder mixed dielectric along with the confirmation tests. Surface characteristics of specimen have also been analyzed using Scanning Electron Microscope (SEM) and Energy Dispersive Spectrograph (EDS).

KEYWORDS: Taguchi Methodology; Microstructure, Crater & Debris

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Original Article

INTRODUCTION

Nickel-based super alloy is used for many typical applications such as for aero engine turbine blades, jet engines as a casing, turbo chargers and pump body parts, because of its improved mechanical and thermal properties. These typical applications required accurate design and close tolerances in manufacturing products. The traditional methods of manufacturing are not capable to machine these alloys, because of such typical properties [1]. The nickel- based super alloy is difficult to machine with traditional machining method due to its high toughness, and poor thermal properties. Because of such limitations, mainly, a non-conventional machining method like electric discharge machining (EDM) is chosen for machining Inconel material [2]. EDM is a technological process and can modify the process variables with the use of powder additives in the EDM oil [3]. In the process of evaluating the performance characteristics of machining of aluminum matrix composites using PMEDM, it is observed that material removal depth hikes with the machining in powder mixed dielectric [4]. Machined the titanium alloy using pure water and SiC powder as a powder additive in EDM oil, and concluded that pure water hikes the MRR along with low electrode wear while with the use of both the additives resulting in high conductivity [5]. Conducted experiments with three different titanium alloys and three electrode materials along with powder additive in the EDM oil. Results indicated that the tool material has the highest effect on SR of

the electrode [6]. Conducted experiments using kerosene as the EDM oil and found that the additives can increase the MRR and decrease the TWR [7]. Compared the EDM process by using different dielectric fluids i.e. kerosene and kerosene with SiC powder. Concluded that kerosene with SiC powder increased the material removal depth and the surface roughness as compared to the machining only in EDM oil [8]. Compared the performance of powder mixed dielectric and with the conventional EDM when dealing with the generation of high-quality surfaces and concluded that the use of PMD-EDM promotes the reduction of surface roughness [9]. Introduced accretion method along with powder additive in the EDM oil. Results indicated that a rotating disk electrode with a column was formed two with powder suspended in the working fluid [10]. Enhanced the surface characteristics of tungsten carbide alloy by using graphite as a powder additive in the EDM oil. The results indicated that T_{on} is the main factor compared to other factors [11]. Proposed a method by using tungsten carbide powder additive in EDM oil. The results indicated the significant improvement in the SR [12]. Studied the powder mixed EDM and its mechanism. Reported that when abrasive powder is mixed in EDM oil, it reduced the insulating strength of EDM oil and hikes the MRR and TWR [13]. Presented with a new method by using μ-MoS_2 powder particles suspended in EDM oil. Results indicated that with the use of MoS_2 micro-powder in dielectric fluid significantly increases the MRR and surface quality [14].

Literature review indicated that very little work has been done on PMEDM of Inconel-600 as compared to the machining of other material also lot of different abrasive powders are used for machining like aluminum powder, silicon carbide, graphite etc, but the effect of powder particle, i.e. tungsten carbide along with tool material i.e. copper on Inconel-600 material has not been reported. The aim of this work is comparing the response characteristics coming from machining with and without powder mixed with EDM oil.

METHODOLOGY AND EXPERIMENTAL SETUP

Methodology

One factor at a time approach is applied to select the factors and levels of the present study. During experimentation parameters such as peak current, T_{on}, T_{off} was varied to find out their effect on the MRR and TWR. Other process parameters such as polarity (anode work piece, cathode tool), machining depth (0.5 mm), and powder concentration (6 g/l) was kept constant during the experimentation. Degrees of freedom for the three factors were calculated to be 8. Thus, the Taguchi L_9 matrix was a suitable design for the present study. The working range and their levels are shown in table 1.

Table 1: Working Range of the Process Parameters and their Levels

S.No	Symbols	Input Factors	Level			Units
			1	2	3	
1	A	T_{on}	60	90	120	μs
2	B	T_{off}	30	45	60	μs
3	C	Current (Ip)	4	8	12	Ampere
4	D	Tool material	Copper			----
5	E	Powder (Suspended particles)	Tungsten carbide			Gram

Experimental Setup

A die sinking EDM machine is used to performed the experiments. The pictorial view of EDM machine is as illustrated in Figure.1 (b). A separate tank having dimension (350×200×200) mm was installed on the machine for mixing powder with the EDM oil along with a stirrer mechanism to avoid settling of powder particles as shown in Figure 1 (a).

Before machining the work pieces and electrode were cleaned with acetone. Chemical composition of work and electrode material is as shown in table 2.

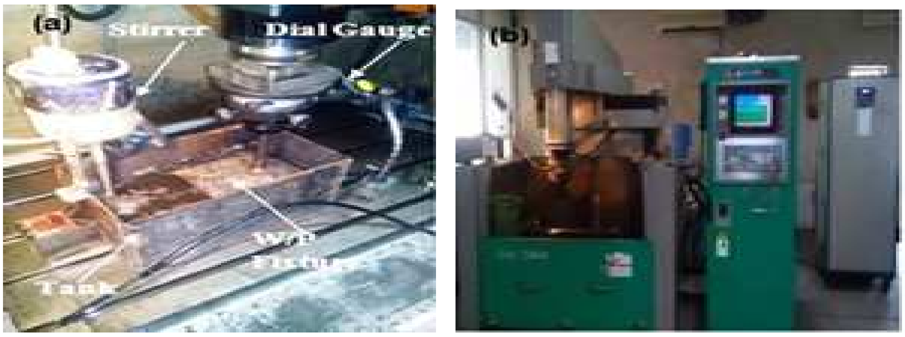

Figure 1: (a) and (b) Experimental Setup for the Machine, Pictorial View of EDM Machine

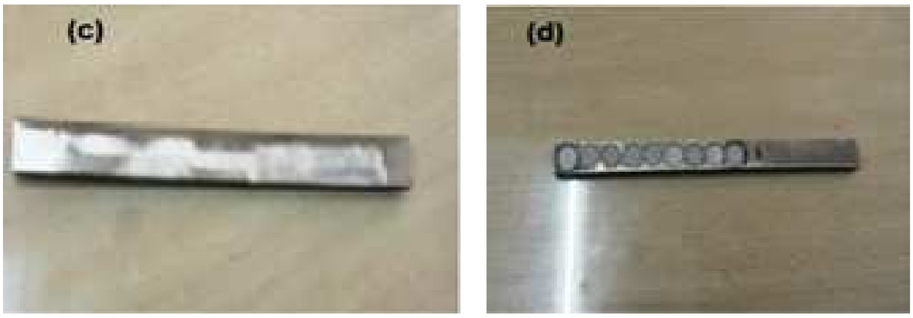

Figure 1: (c) and (d) Workpiece Specimen before Machining and Workpiece Specimen after Machining

Table 2: Chemical Composition of Work and Electrode Material

Work Material			Electrode Material
Elements	**Inconel-600**		**Copper**
Ni	Base material		0.0083
Fe	7.78		0.109
Cu	0.5		99.7
Si	0.5		< 0.0050
Cr	14.56		0.0061
Al	_		< 0.0020
S	< 0.015		< 0.0020
Bi	_		< 0.0050
Sb	_		< 0.0050
Zn	_		0.0148
Pb	_		0.0206
Sn	_		0.0356
Mn	< 1.0		0.005
C	< 0.15		

The work material has been taken in the form of rectangular plate having dimensions 150 mm × 15 mm × 6 mm. The work piece material before and after machining as shown in Figure 1 (c) and (d).

RESULTS AND DISCUSSIONS

Analysis of Material Removal Rate and Tool Wear Rate

Analysis of variance has been done using Taguchi method of MINITAB software. The values of MRR for orthogonal L_9 arrey based on experimental results with three repetitions without and with powder mixing along with S/N ratio is shown in Table 3. The overall mean of MRR, without powder is 14.09 mm^3/min while with powder, it is 20.17 mm^3/min. Means of signal to noise ratio without powder of MRR is 20.66 while with powder is 13.47. For MRR value of R^2 and R^2 (adj) is 99.2% and 96.9% without powder mixing while value of R^2 and R^2 (adj) is 99.9% and 99.4% with powder mixing. Table 4 shows the orthogonal array based on experimental average results of TWR, without powder mixing with EDM oil and with powder mixing in EDM oil along with S/N ratio. The overall mean of TWR, without powder is 0.187 while with powder is 22.57. Means of signal to noise ratio without powder of TWR is 21.96 while with powder is.121. For TWR value of R^2 and R^2 (adj) is 82.9% and 31.7% without powder mixing while the value of R^2 and R^2 (adj) is 96.0% and 84.0% with powder mixing.

Table 3: Average Results of MRR Without and With Powder Mixing along with S/N Ratio

Material Removal Rate (mm3/Min) Without Powder Mixing With EDM Oil								
Exp. No	Levels of Parameters			Material Removal Rate			Mean Value	S/N Ratio
	A	B	C	R-1	R-2	R-3		
1	60	30	4	4.224	4.24	4.224	4.229	12.52
2	60	45	8	11.694	11.65	11.694	11.679	21.35
3	60	60	12	14.456	14.515	14.485	14.485	23.22
4	90	30	8	16.222	16.163	16.163	16.182	24.18
5	90	45	12	27.371	27.467	27.467	27.435	28.77
6	90	60	4	3.181	3.162	3.162	3.168	10.02
7	120	30	12	40.616	40.691	40.616	40.641	32.18
8	120	45	4	3.932	3.948	3.948	3.942	11.91
9	120	60	8	12.365	12.365	12.365	12.365	21.84
Overall mean of MRR without powder = 14.90 R^2 = 99.2% R^2 (adj) = 96.9%							Mean of S/N ratio m = 20.66	
Material Removal Rate (mm3/Min) With Powder Mixing With EDM Oil								
1	60	30	4	3.839	3.821	3.839	3.833	11.67
2	60	45	8	10.666	10.712	10.689	10.689	20.578
3	60	60	12	16.59	16.59	16.59	16.59	24.396
4	90	30	8	15.058	14.999	14.999	15.018	23.532
5	90	45	12	26.177	26.283	26.23	26.23	28.375
6	90	60	4	3.025	3.025	3.032	3.027	9.62
7	120	30	12	29.897	29.838	29.838	29.857	29.5
8	120	45	4	4.138	4.129	4.138	4.135	12.329
9	120	60	8	11.9	11.947	11.924	11.923	21.527
Overall mean of MRR with powder = 20.17 R^2 = 99.9% R^2 (adj) = 99.4%							Mean of S/N ratio m = 13.47	

From the table 3 and 4, it is observed that the average value of signal to noise ratio increased when tungsten carbide is used as a powder additive. This means MRR increased with the use of tungsten carbide as a powder additive in the EDM oil. The overall means of TWR is increased, while means of signal to noise ratio decreased when tungsten carbide is used as a powder additive in EDM oil. Also with the use of tungsten carbide powder as an additive in the EDM oil, increases the value of R^2 and R^2 (adj.). The analysis of variance (ANOVA) results of MRR and TWR, without powder mixing in EDM oil and with powder mixing in EDM oil is shown in table 5 and 6. According to ANOVA and F-test values

current is the most vital factor for both MRR and TWR as compared to other factors i.e. T_{on} and T_{off}. With the use of powder additive for MRR, residual error reduced to 0.7% to 0.1%, while for TWR it reduced to 17% to 3.9% as shown in table 5 and 6

Table 4: Average Results of TWR Without and With Powder Mixing Along With S/N Ratio

Tool Wear Rate (mm3/Min) Without Powder Mixing With EDM Oil								
Exp. No	**Levels of Parameters**			**Tool Wear Rate**			**Mean Value**	**S/N Ratio**
	A	**B**	**C**	**R-1**	**R-2**	**R-3**		
1	60	30	4	0.015	0.007	0.007	0.009	40.915
2	60	45	8	0.021	0.042	0.021	0.028	31.056
3	60	60	12	0.78	0.752	0.752	0.761	2.372
4	90	30	8	0.083	0.139	0.139	0.12	18.444
5	90	45	12	0.182	0.136	0.136	0.151	16.42
6	90	60	4	0.03	0.036	0.036	0.034	29.37
7	120	30	12	0.491	0.491	0.491	0.491	6.178
8	120	45	4	0.044	0.044	0.044	0.044	27.13
9	120	60	8	0.066	0.044	0.044	0.051	25.848
Overall mean of TWR without powder = 0.187 R^2 = 82.9% R^2 (adj) = 31.7%						Mean of S/N ratio m = 21.96		
Tool Wear Rate (mm3/Min) With Powder Mixing in EDM Oil								
1	60	30	4	0.024	0.033	0.016	0.024	32.395
2	60	45	8	0.086	0.107	0.129	0.107	19.419
3	60	60	12	0.39	0.39	0.39	0.39	8.178
4	90	30	8	0.138	0.138	0.138	0.138	17.202
5	90	45	12	0.252	0.202	0.202	0.218	13.23
6	90	60	4	0.029	0.035	0.029	0.031	30.172
7	120	30	12	0.111	0.111	0.166	0.129	17.789
8	120	45	4	0.016	0.016	0.016	0.016	35.917
9	120	60	8	0.044	0.044	0.022	0.036	28.873
Overall mean of TWR with powder =.121 R^2 = 96.0% R^2 (adj) = 84.0%						Mean of S/N ratio m = 22.57		

Figure 2 (a) and (b) show the MRR graph plots of main effects of means of means, without and with powder mixing. From the figure, it is clear that with the increase of current, MRR is increased. As the current is higher the discharge energy is also higher.

Table 5: ANOVA Analysis for MRR without and with Powder

ANOVA for MRR Without Powder Mixing in EDM Oil								
Control Factors	**DOF**	**Seq. SS**	**Adj. SS**	**Adj. MS**	**F-value**	**P-value**	**% PC**	**Remarks**
A	2	13.5	13.5	6.754	3.72	0.103	2.8	√
B	2	31.77	31.77	15.886	8.75	0.008	6.6	√√
C	2	426.2	426.2	213.13	117.4	0.007	89.7	√√√
Residual Error	2	3.629	3.629	1.814			0.7	
Total	**8**	**475.1**						
ANOVA for MRR With Powder Mixing in EDM Oil								
A	2	8.025	8.025	4.01	13	0.071	1.8	√
B	2	14.28	14.28	7.14	23.13	0.041	3.3	√√
C	2	407.6	407.6	203.8	660.2	0.002	94.6	√√√
Residual Error	2	0.617	0.617	0.309			0.1	
Total	**8**	**430.5**						

x- not significant, √ - less significant, √√- significant, √√√-most significant

Therefore when discharge energy is high resulting melting temperature is also high causes evaporation and greater impulsive forces acting on machine area resulting higher MRR [10]. Optimum parameters obtained for MRR with powder additives are $A_3B_1C_3$.

Percentage contribution of current is highest in both the cases i.e. MRR and TWR as shown in table 5 and 6. From the table 5, for MRR it is clear that without powder, percentage contribution of current is 89.7 % while with powder contribution of current is 94.6%. This means more MRR is obtained with the use of tungsten carbide as a powder additive. From table 6, for TWR it is clear that without powder percentage contribution of current is 75.6 % while with powder contribution of current is 80.7 %. Percentage contribution of T_{on} and T_{off} for MRR is 2.8 and 6.6 without powder mixing while with powder mixing, contribution is 1.8 and 3.3 as shown in table 5. From the table 6, it has been found that percentage contribution of T_{on} and T_{off} for TWR is 3.2 and 3.9 without powder mixing while with powder mixing, contribution is 15.1 and 0.04.

Table 6: ANOVA Analysis for TWR Without and With Powder

ANOVA for TWR Without Powder Mixing In EDM Oil								
Control Factors	**DOF**	**Seq. SS**	**Adj. SS**	**Adj. MS**	**F-value**	**P-value**	**%PC**	**Remarks**
A	2	39.88	39.88	19.94	0.19	0.839	3.2	√√
B	2	48.34	48.34	24.17	0.23	0.811	3.9	√
C	2	919.08	919.08	459.54	4.43	0.184	75.6	√√√
Residual Error	2	207.51	207.51	103.76			17	
Total	**8**	**1214.8**						
ANOVA for TWR With Powder Mixing With EDM Oil								
A	2	110.4	110.4	55.204	3.79	0.209	15.1	√√
B	2	0.354	0.354	0.117	0.01	0.988	.04	√
C	2	588.35	588.35	294.17	20.21	0.047	80.7	√√√
Residual Error	2	29.11	29.11	14.555			3.9	
Total	**8**	**728.22**						

The response values for S/N ratio for each level of identifying factors have been listed in Table 7 which shows the factor level values of each factor and their ranking.

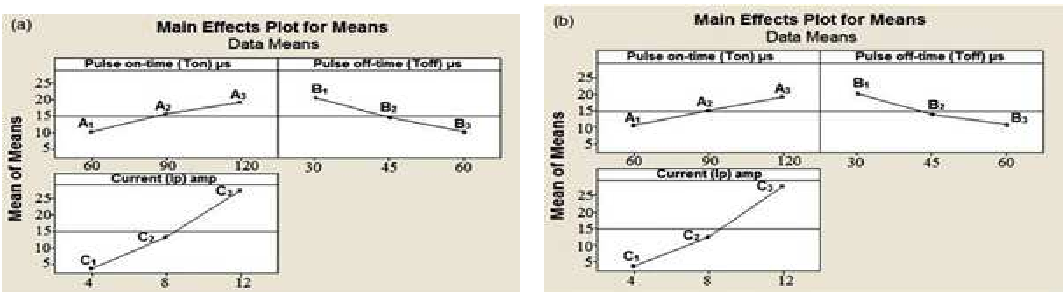

Figure 2 (a): Main Effects Plot for Means of (b) Main Effects Plot for Means of MRR Without Powder MRR With Powder

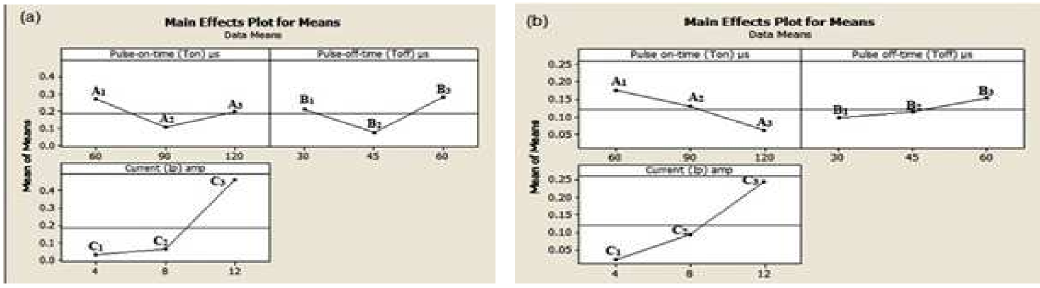

Figure 3 (a): Main Effects Plot for Means of TWR (b) Main Effects Plot for Means of TWR Without Powder With Powder

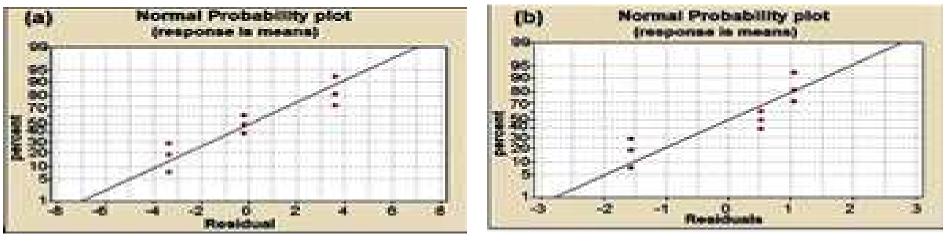

Figure 4: (a) and (b) Normal Probability Plot for MRR With and Without Powder

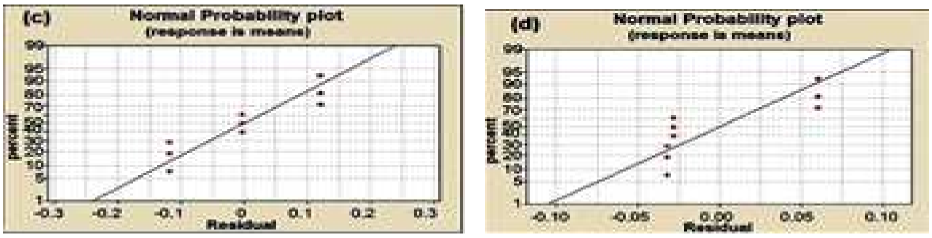

Figure 4:(c) and (d) Normal Probability Plot for TWR With and Without Powder

Table 7: Response Table for Signal to Noise Ratio of MRR and TWR

Delta/Rank for MRR Without Powder					Delta/Rank for TWR Without Powder			
Level	**A**	**B**	**C**		**Level**	**A**	**B**	**C**
1	19.03	22.96	11.48		1	19.03	22.96	11.48
2	20.99	20.68	22.46		2	20.99	20.68	22.46
3	21.98	18.36	28.05		3	21.98	18.36	28.05
Delta	2.95	4.6	16.57		Delta	2.95	4.6	16.57
Rank	3	2	1		Rank	3	2	1
Delta/Rank for MRR With Powder					**Delta/Rank for TWR With Powder**			
1	18.88	21.57	11.21		1	18.88	21.57	11.21
2	20.51	20.43	21.88		2	20.51	20.43	21.88
3	21.12	18.51	27.42		3	21.12	18.51	27.42
Delta	2.24	3.05	16.22		Delta	2.24	3.05	16.22
Rank	3	2	1		Rank	3	2	1

Figure 3 (a) and (b) shows the graph plots of main effects of means of means, without and with powder mixing. From the figure, it is clear that with the use of tungsten carbide as a powder additive, reduce the TWR. Optimum parameters obtained for TWR with powder additives are $A_3B_1C_1$. The residual plots for MRR and TWR for 9 trials along with and without powder are shown in Figure. 4 (a-d).

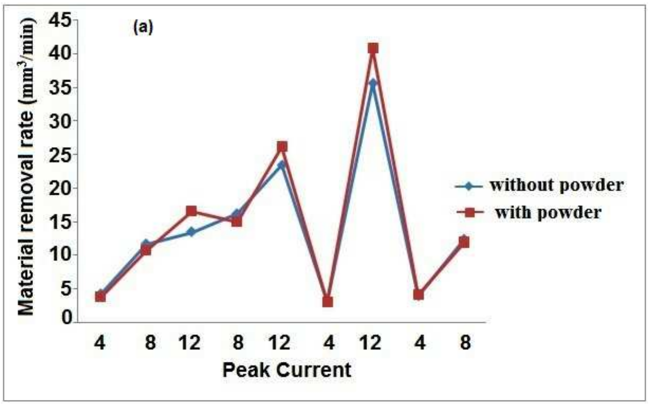

Figure 5 (a): Performance Comparision Graph for MRR (With and Without Powder)

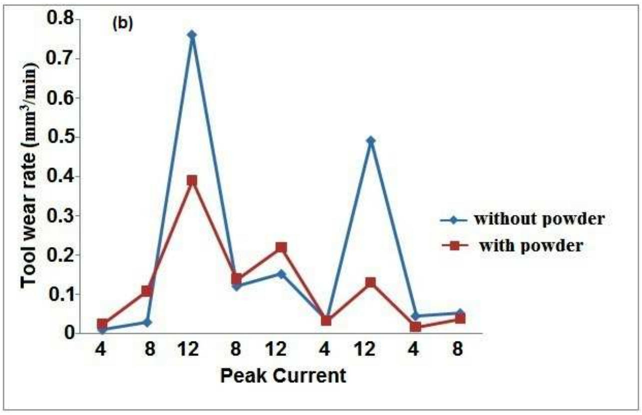

Figure 5 (b): Performance Comparison Graph for TWR (With and Without Powder)

Figure 5 (a) shows the performance comparison graph for MRR (with and without powder). It is clear from the figure that with the use of tungsten carbide as a powder additive in EDM oil, MRR increases as compared to MRR without powder. From the performance graph, it is clear that with the use of powder additive tool wear rate decreases as shown in Fgure 5 (b).

Microstructure Analysis

Figure 6 (a) and (b) shows the SEM micrographs of Inconel-600 material.

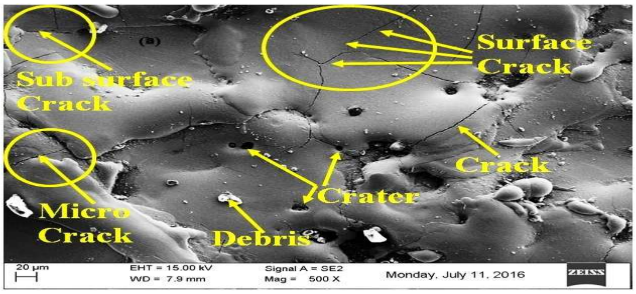

Figure 6: (a) SEM Micrograph of Inconel-600 at T_{on}= 120 µs, T_{off}= 60 µs, I_p= 12 amp, Copper as a Tool Material and Without Powder Mixing With the EDM Oil

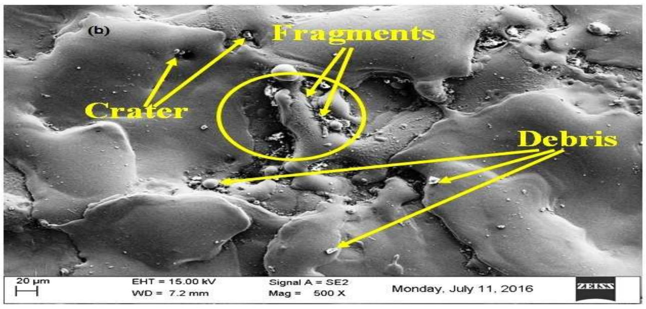

Figure 6 (b): SEM Micrograph of Inconel-600 at T_{on}= 120 µs, T_{off}= 60 µs, I_p= 12 amp, Copper as a Tool Material and With Tungsten Carbide Powder Mixing in the EDM Oil

SEM micrograph of work specimen which is machined without powder additive in the EDM oil as shown in Figure 6 (a) while SEM micrograph of work specimen which is machined with tungsten carbide as a powder additive as shown in Figure 6 (b). Other input process parameters are constant for both the specimens, i.e. T_{on} = 120 µs, T_{off} = 60 µs and current = 12 amp and copper as a tool material. From the Figure. 6 (a), it is observed that when machining is done without powder mixing, surface crack, microcracks, sub-surface crack, crate and debris are formed while with powder mixing, crate and debris are formed.

EDX Analysis

This technique is used to recognize the elemental composition of the machined specimen. With the continuous flow of dielectric fluid, the metal particles are flushed out from the machined specimen. Some material particles are left on the machined specimen surface, because of the particles that cannot be transported completely of the discharge gap. EDX results show the improved quality and quantity values of elemental composition of the Inconel-600 work piece. Figure 7 (a) and (b) compares the EDX pattern of without and with powder additives machining samples, in order to investigate the chemical composition.

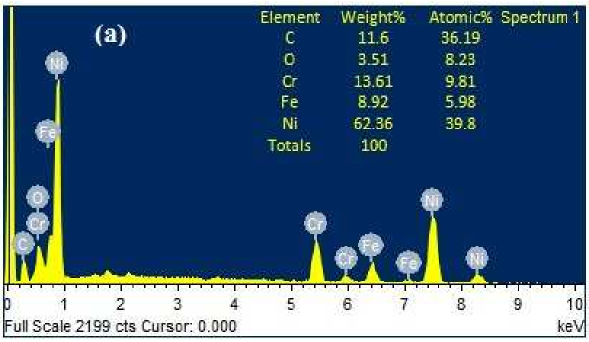

Figure 7 (a): EDX Analysis of Inconel-600, Machining Condition at T_{on}= 120 µs, T_{off}= 60 µs, I_p= 12 Amp,Copper as a Tool Material and Without Powder Mixing With the EDM Oil

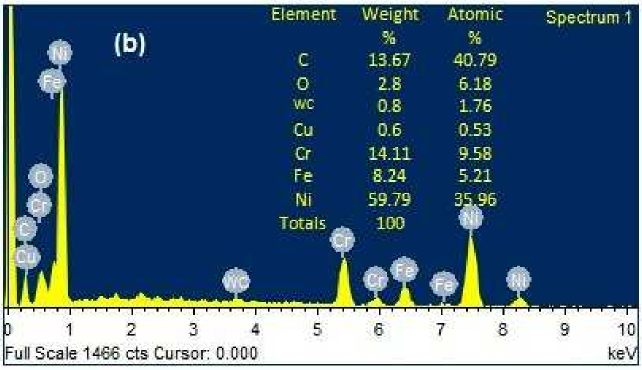

Figure 7: (b) EDX Analysis of Inconel-600, Machining Condition at T_{on}= 120 µs, T_{off}= 60 µs, I_p= 12 Amp, Copper as a Tool Material and With Powder Mixing with the EDM Oil

Machining without powder additive, the wt % of particles are C= 11.06, O= 3.51, Cr= 13.61, Fe= 8.92 and Ni= 62.36 as shown in Figure. 7 (a). Machining with powder additive, the weight percentage of an element changes to C= 11.06 to 13.67, O= 3.51 to 2.8, Cr= 13.61 to 14.11, Fe= 8.92 to 8.24, Ni= 62.36 to 59.79, Cu= 0.6 and WC= 0.8 as illustrated in Figure. 7 (b). With EDX analysis, the residuals of Tungsten carbide (WC), Carbon (c) and Copper (Cu) were identified in the machined specimen with powder additive. This may be due to the melting and re-solidification of the tool material and powder particles suspended in EDM oil.

CONCLUSIONS

In the present study, Inconel-600 a super alloy was machined with copper (Cu) as a tool material in the presence of tungsten carbide powder mixed dielectric fluid with different machined input parameters. Vital parameters that affect the output characteristics while machining were detected using ANOVA. From the result of ANOVA, current (C) has the highest effect on MMR of workpiece material and tool wear of the electrode. From the experimentation, it is concluded that the use of tungsten carbide as a powder additive with EDM oil enhances the response parameters, i.e. increases the MRR and decreases the TWR.

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